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## Scrape-off layer power fall-off length from turbulence simulations

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### Introduction

In magnetic confinement fusion devices, most of the power across the last-closed flux surface (LCFS) is transported towards the divertor along a narrow channel in the scrape-off layer (SOL). The width of this channel is denoted as  $\lambda_q$  and extensive experimental studies of the scaling of this parameter are found in the literature (see e.g. [1–4]), however, a theoretical understanding of what constitutes  $\lambda_q$  is still missing. We therefore investigate the scaling of this SOL power fall-off length by means of numerical simulations. This is done using the HESEL model [5], a four-field 2D drift-fluid model solving for the density,  $n$ , generalised vorticity,  $\omega^*$ , electron pressure,  $p_e$ , and ion pressure,  $p_i$ , in a domain at the outboard mid-plane.

A scan of the toroidal magnetic field,  $B$ , the safety factor,  $q$ , and the total power crossing the LCFS,  $P_{tot}$ , is performed using parameters relevant for ASDEX Upgrade (AUG), COMPASS and JET L-mode plasmas. For AUG parameters we find a scaling law given by

$$\lambda_q = (1.19 \pm 0.28) P_{tot}^{-0.22 \pm 0.05} q^{1.12 \pm 0.11} B^{-0.2 \pm 0.13}, \quad (1)$$

which is close to the experimental scaling found in [2] with a weak inverse dependence on  $P$  and an almost linear dependence on  $q$  (note that  $B^{-0.78}$  in [2], but this is taken directly from the H-mode scaling in [1], and is thus not a fitted parameter). When including all three machines, a multi-machine scaling for  $\lambda_q$  is found to be

$$\lambda_q = (1.63 \pm 0.18) P_{tot}^{-0.36 \pm 0.06} q^{1.38 \pm 0.15} B^{0.27 \pm 0.12} R^{1.63 \pm 0.18}, \quad (2)$$

where we also find a weak inverse dependence on  $P_{tot}$  and an almost linear dependence on  $q$ . The sign on the exponent on  $B$ , however, has an opposite sign of the AUG scaling and we find a large dependence on the major radius,  $R$ , where the experimental scaling in [3] only shows a weak dependence on  $R$ . This difference may be attributed to a difference in the level of turbulence between the three simulations. At the time of writing, a numerical investigation of the dependence of  $\lambda_q$  on  $R$  is being conducted.

### The HESEL model

HESEL (Hot ions Edge Scrape-off layer Electrostatic turbulence) is a four field model based on the Braginskii two-fluid equations. The model solves for the density,  $n$ , generalised vorticity,  $\omega^*$ , electron pressure,  $p_e$ , and ion pressure,  $p_i$ , at the outboard mid-plane of a tokamak, with the domain as illustrated in figure 1. The domain includes the edge and SOL regions and the turbulence and power flux are sustained keeping the profiles at the inner boundaries in the edge region close to a prescribed profile.

The parallel heat fluxes for the HESEL model consist of three contributions, the electron conduction (Spitzer-Harm conduction),  $P_{SH}$ , electron advection  $P_{pe}$  and ion advection  $P_{pi}$ , which are given by

$$P_{SH} = \left\langle \frac{p_e}{\tau_e} \right\rangle, \quad \tau_e = \frac{3}{2} L_B^2 v_{ee} \frac{1 + \frac{3.2}{0.8 v_{es}^*}}{3.2 v_e^2} \propto \bar{T}_e^{-5/2}$$

$$P_{pe} = \left\langle \frac{9}{2} \frac{p_e}{\tau_s} \right\rangle, \quad \tau_s = \frac{L_B}{M c_s} \propto \bar{T}_e^{-1/2}$$

$$P_{pi} = \left\langle \frac{9}{2} \frac{p_i}{\tau_s} \right\rangle.$$

Here  $\langle . \rangle$  denotes a temporal average,  $\bar{T}_e$  is the electron temperature normalised to the background temperature,  $p_e$  is the electron pressure and  $p_i$  is the ion pressure.  $L_B = qR$  is the ballooning length,  $v_{ee}$  is the electron-electron collision frequency,  $v_{es}^*$  is the electron collisionality,  $v_e$  is the electron thermal velocity,  $M$  is the Mach number and  $c_s$  is the sound speed. In order to relate the heat fluxes in the above equations to the experimentally found power profiles, we assume that the heat flux across the LCFS is concentrated in the ballooning region. This implies that we estimate the power across the LCFS by integrating over the total ballooning region. The total unstable ballooning region is given by  $A_{ball} = 2\pi(R+a)a$ , where  $R$  is the major radius of the device and  $a$  is the minor radius. The estimated total radial power profile at the outer mid-plane is then given by  $P_{tot} = A_{ball} (P_{SH} + P_{pe} + P_{pi})$ .

These powers can now be plotted as a function of the radial position at the outboard mid-plane, which is what is seen in Fig. 2. The plot shows typical power profiles for AUG relevant parameters from a HESEL simulation. The solid blue line indicates the contribution from the electron conduction, the dashed blue line is the contribution from the electron advection and the

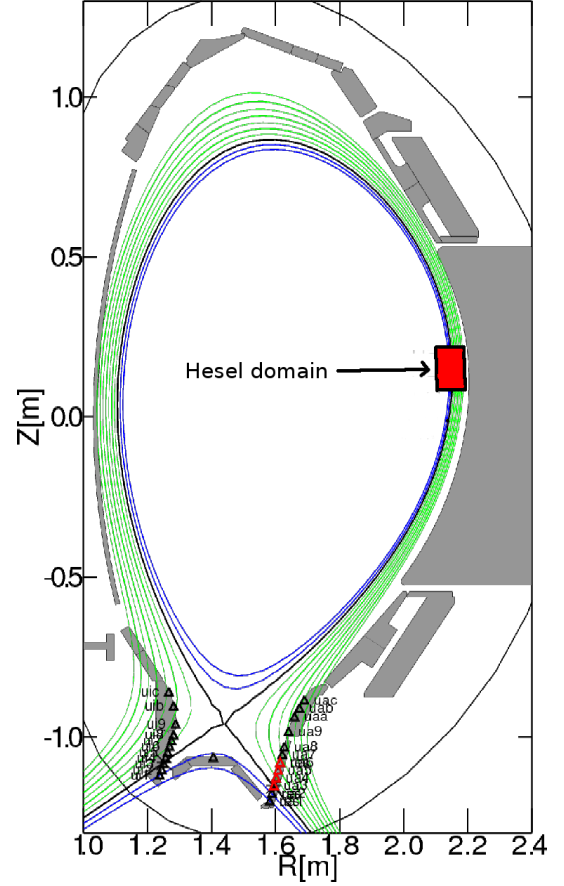
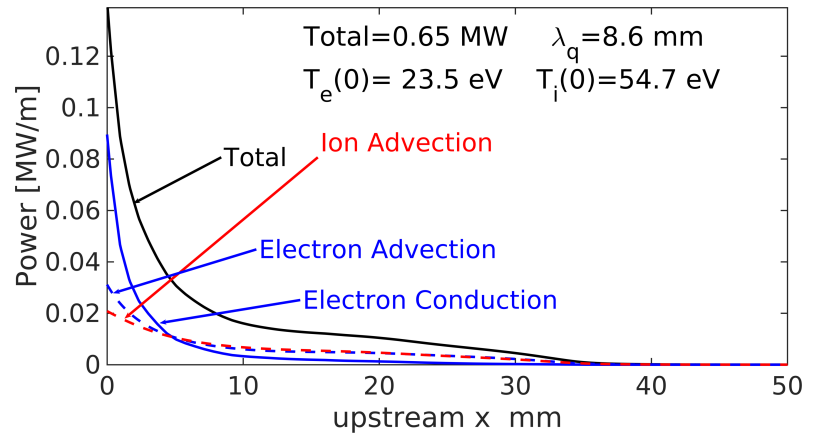


Figure 1: A cross-section of the AUG tokamak. The HESEL domain is illustrated using the red box.

dashed red line is the contribution from the ion advection.

What we see is that close to the LCFS the electron conduction dominates the power loss, but further into the SOL, the electron and ion advection take over as the dominant contributions to the power flux, which leads to a total power, resembling an exponential function

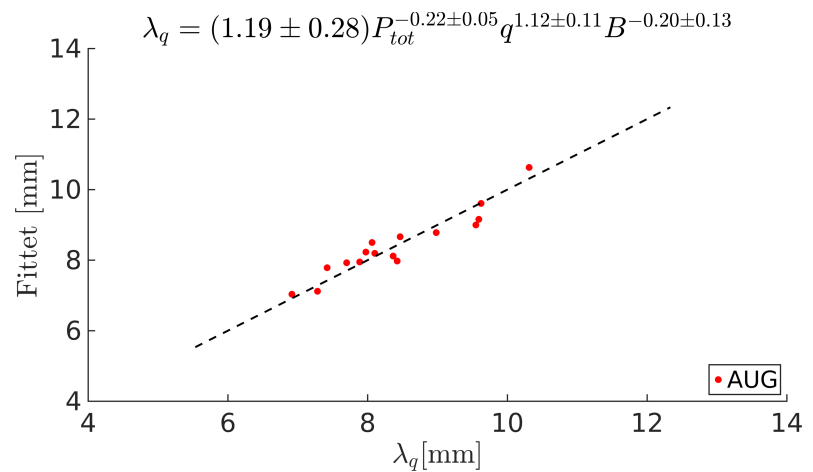


close to the LCFS but with a long tail. The power fall-off length,  $\lambda_q$ , is then calculated using the weighted average position of the total power flux, so  $\lambda_q = \langle x P_{tot}(x) \rangle_x / \langle P_{tot}(x) \rangle_x$ , where  $P_{tot}(x)$  is the radial power profile,  $x$  is the radial position and  $\langle \cdot \rangle_x$  denotes a spatial average.

### Numerical power fall-off length scaling

By varying the input parameters,  $B$ , in the range [1.5 T, 2.3 T] and  $q$  in the range [3.8, 6] and varying  $P$  in the range [0.15 MW, 0.65 MW] by fixing different temperature profiles at the inner boundaries in the HESEL simulations,  $\lambda_q$  was calculated for a number of L-mode cases using AUG parameters. The resulting values for  $\lambda_q$  are fitted with respect to the scanned parameters, which leads to the scaling seen in Fig. 3.

We observe that all points are very close to the dashed line, which means that the fit almost describes all the variation of the measured  $\lambda_q$  values. This implies that the scrape-off layer power decay length is very weakly dependent on the total power crossing the LCFS,



$P_{tot}$ , and scales almost linearly with the safety factor,  $q$ . We

observe a scaling which is weakly dependent on the toroidal magnetic field,  $B$  in contrast to  $B^{-0.78}$  as used in [2], but this value is taken from a previous study of H-mode discharges and it

is not a scaled parameter.

Finally, we have investigated how  $\lambda_q$  scales when including parameters relevant for 3 different machines, namely COMPASS, AUG and JET. For these machines, the range of  $B$  is [0.7 T, 2.3 T], the range of  $q$  is [3, 6], the range of  $P_{tot}$  is [0.03 MW, 4.4 MW] and the range of  $R$  is [0.56, 2.95]. Using these parameters, we arrive at the scaling shown in Fig. 4.

Again, we observe a weak dependence on  $P_{tot}$  and an almost linear dependence on  $q$ . However, we observe a change in the sign of the exponent on the scaling with  $B$  and we observe a large dependence on the major radius,  $R$ , which contradicts what was found experimentally in [3]. The same trend is found when excluding the COMPASS simulations in the

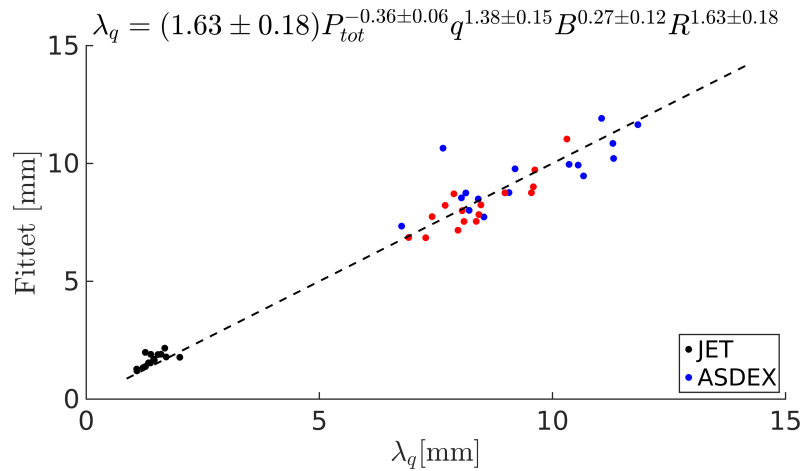


Figure 4:  $\lambda_q$ -fit with HESEL parameters plotted against  $\lambda_q$  obtained with HESEL for COMPASS, AUG and JET

power law, using only values from AUG and JET simulations. However, it should be noted that there is a significant difference in the turbulence levels between the simulations of the three machines. The exponents of  $P_{tot}$  and  $q$  are similar in the scaling laws for the individual machines, but  $\lambda_q$  is smaller by a constant factor between each scaling law, which may be attributed to the difference in the degree of turbulent transport, and which may explain the dependence on  $R$ . At the time of writing, numerical investigations solely varying  $R$  are being conducted in order to rigorously investigate the dependence of  $\lambda_q$  on  $R$ .

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